Computation of CMB-LSS XC spectra in EFT Cosmologies-II

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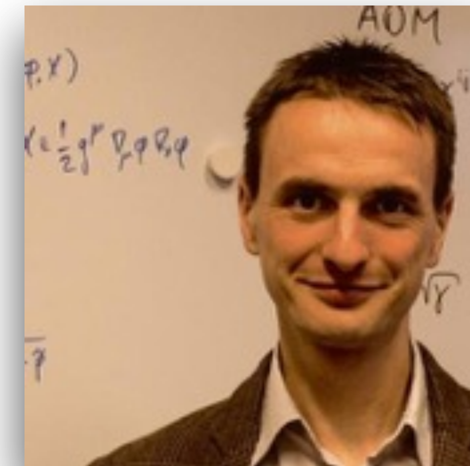
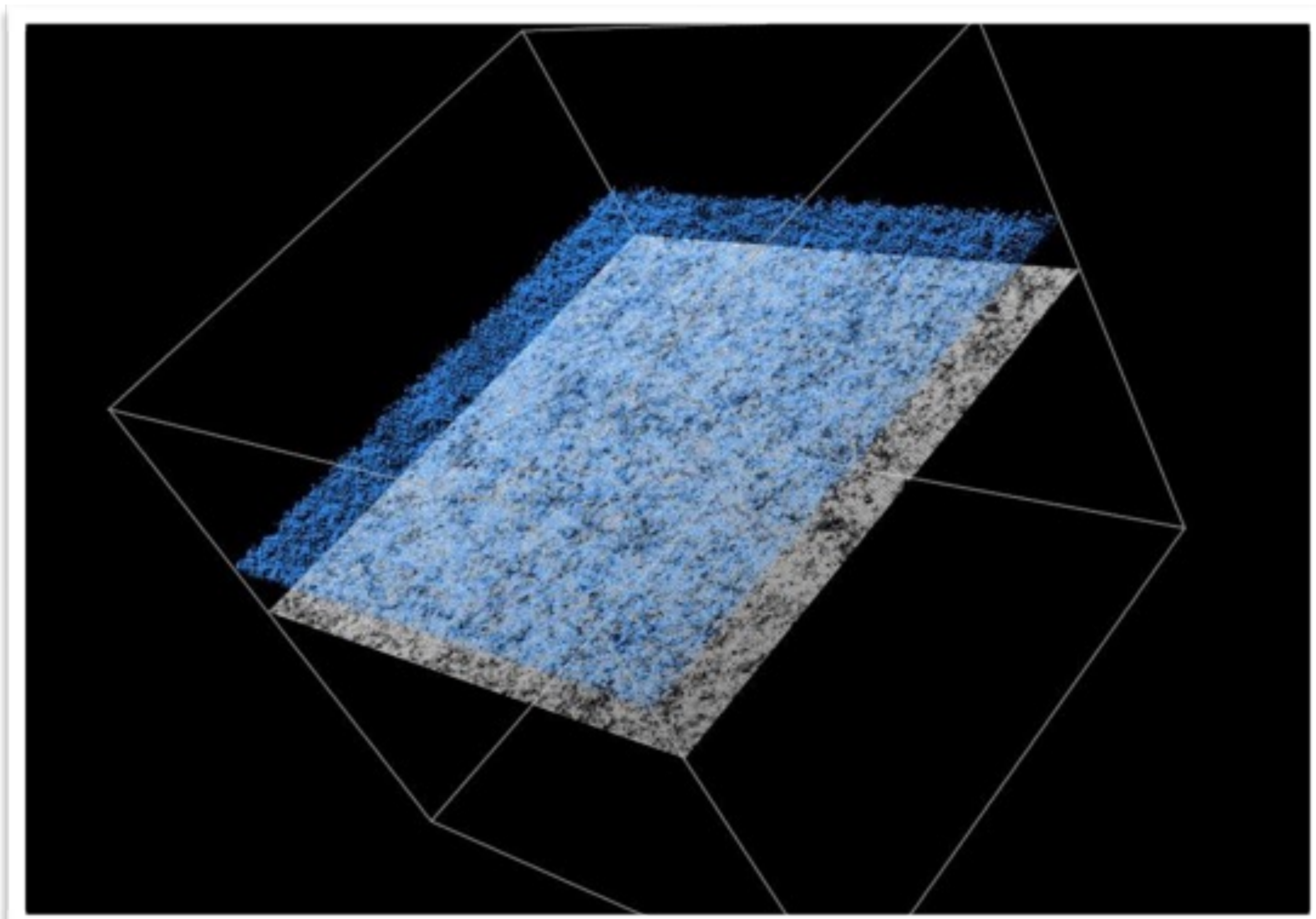
The interface between **EFTCAMB** with IC of N-body simulation of DE/MG— **FalconIC**



C++ code



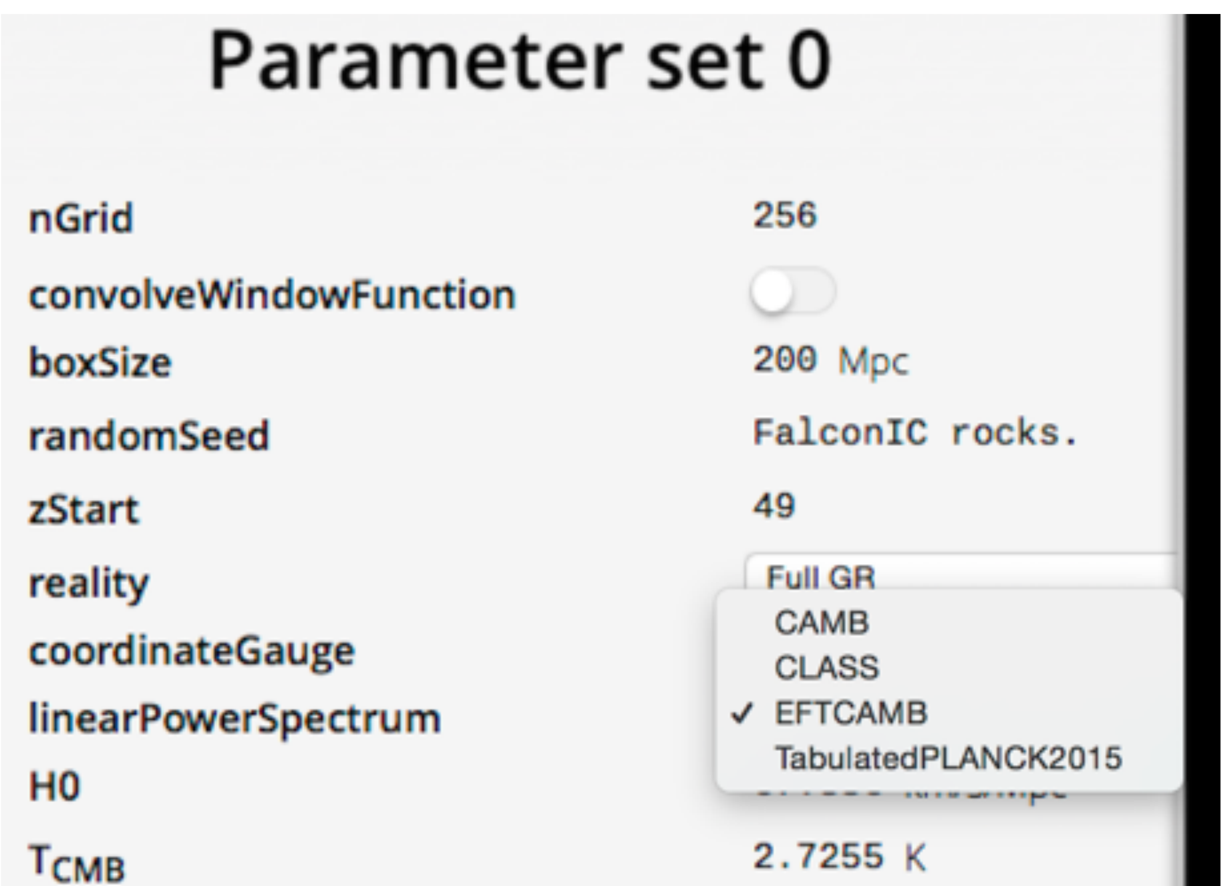
[http://falconic.org]

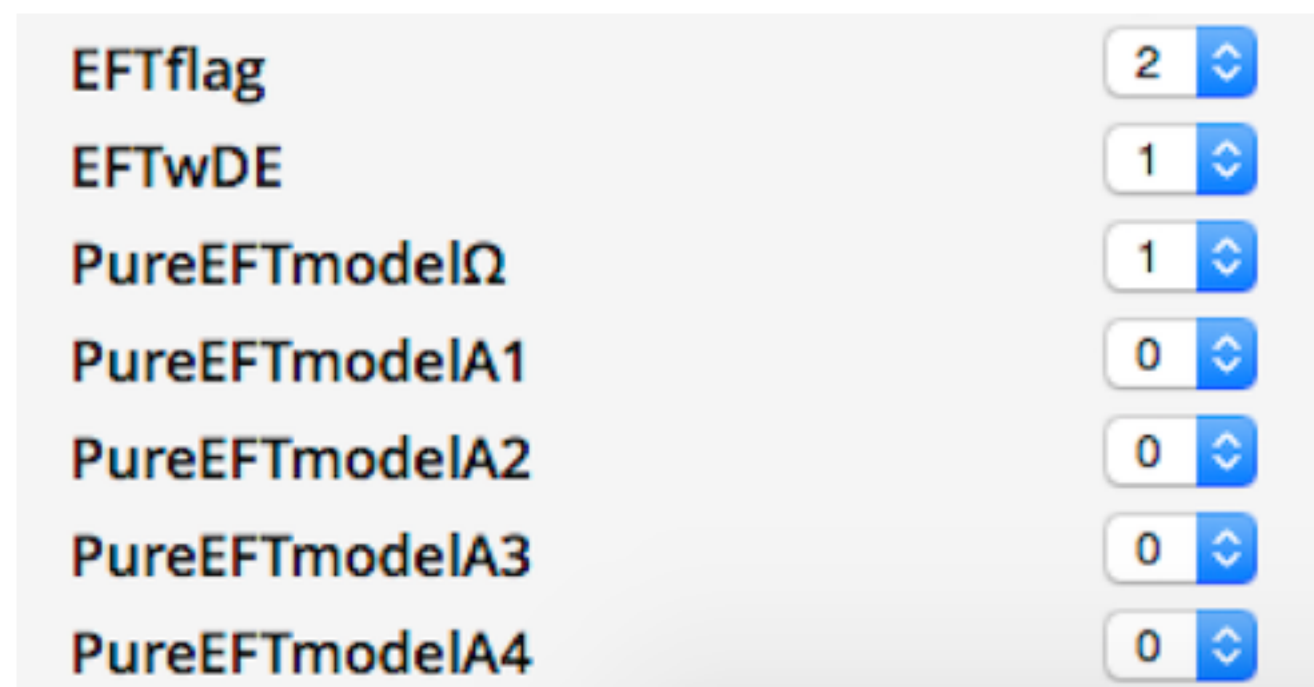
[Wessel Valkenburg, BH, arXiv:1505.05865]

FalconIC

(developed by Wessel Valkenburg)

- Integrated with CAMB/CLASS/EFTCAMB
- Work for GR and DE/MG model
- Generates IC at arbitrary scales, of arbitrary size
- Compile with MPI and OpenMP





Zeldovich Approximation

In the sub-Horizon regime, GR gives

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\rho_m\delta_m = 0$$

The growth rate of CDM only depends on time!

The displacement field $\vec{x} = \vec{y} - \mathcal{D}(\tau)\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i, \vec{y})$

In GR: CDM particles trajectory is straight line!

$$k^2\psi = -4\pi G\,\mu(a,k)a^2\rho\Delta\ ,$$
$$\frac{\phi}{\psi} = \gamma(a,k)\ .$$

DE/MG:

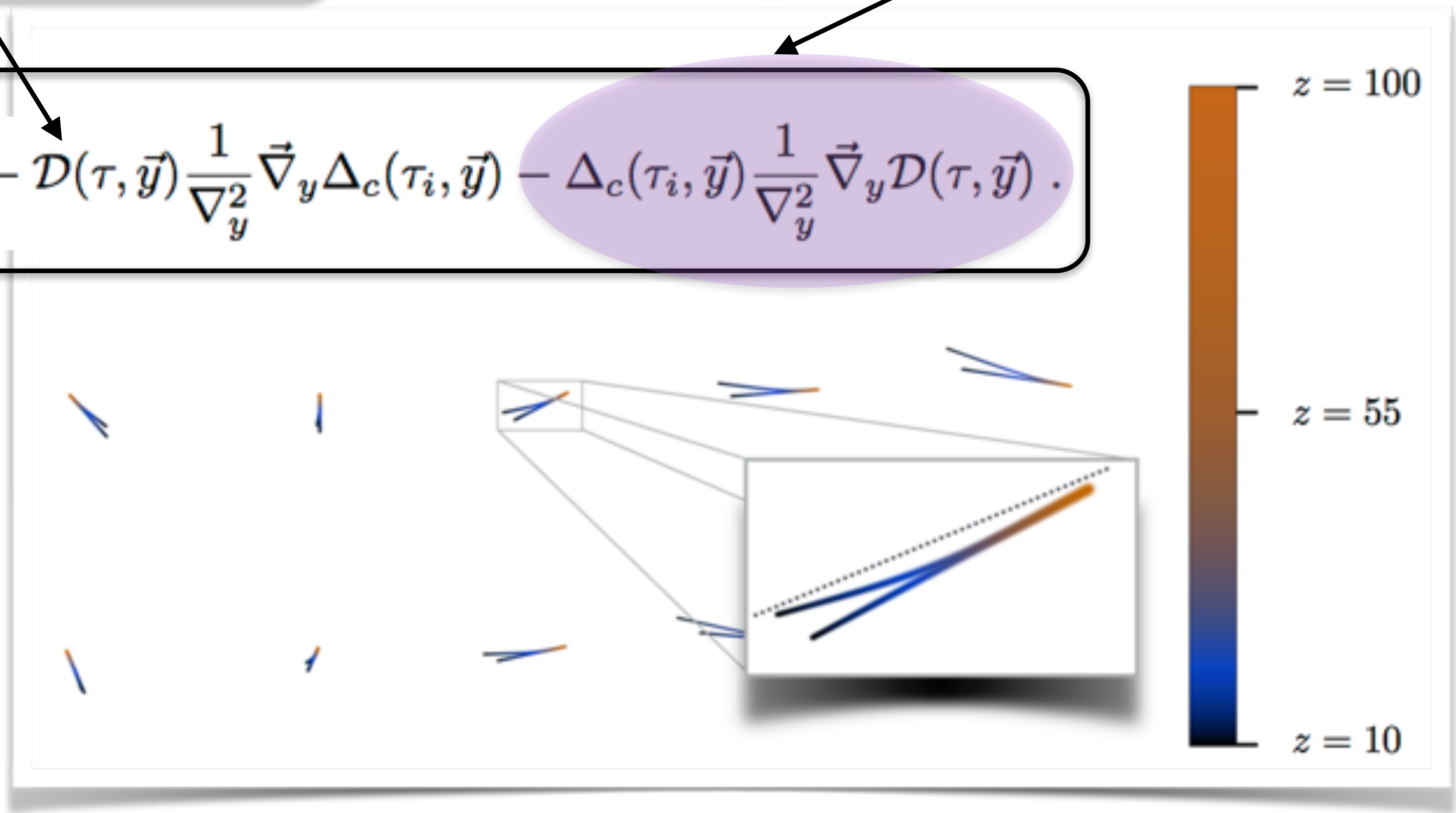
$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\text{eff}}(t,k)\rho_m\delta_m = 0$$

Beyond Zeldovich Approximation

DE/MG: at linear regime
growth rate of CDM
depends on the scales!

Deflection by the
gravitational potential

$$\vec{x} = \vec{y} - \mathcal{D}(\tau, \vec{y}) \frac{1}{\nabla_y^2} \vec{\nabla}_y \Delta_c(\tau_i, \vec{y}) - \Delta_c(\tau_i, \vec{y}) \frac{1}{\nabla_y^2} \vec{\nabla}_y \mathcal{D}(\tau, \vec{y}) \; .$$



Even at linear regime,
trajectory of CDM particles are curved!

Modified Einstein Eq.

$$m_0^2(1+\Omega)G_{\mu\nu}[g_{\mu\nu}] = T^{(m)}_{\mu\nu}[\rho_m, \theta_m, \cdots] + T^{(\pi)}_{\mu\nu}[\pi, \dot{\pi}, \cdots] \ ,$$

Define a conserved Fluid EMT ($\nabla^\nu T^{(Q)}_{\mu\nu} = 0$)

$$\boxed{\begin{aligned} m_0^2 G_{\mu\nu}[g_{\mu\nu}] &= T^{(m)}_{\mu\nu}[\rho_m, \theta_m, \cdots] + T^{(Q)}_{\mu\nu}[\rho_\pi, \theta_\pi, \rho_m, \cdots] \ , \\ T^{(Q)}_{\mu\nu}[\rho_\pi, \theta_\pi, \rho_m, \cdots] &\equiv \frac{1}{1+\Omega}\Big\{ -\Omega T^{(m)}_{\mu\nu}[\rho_m, \theta_m, \cdots] + T^{(\pi)}_{\mu\nu}[\pi, \dot{\pi}, \cdots] \Big\} \ . \end{aligned}}$$

At linear order the fluid variables

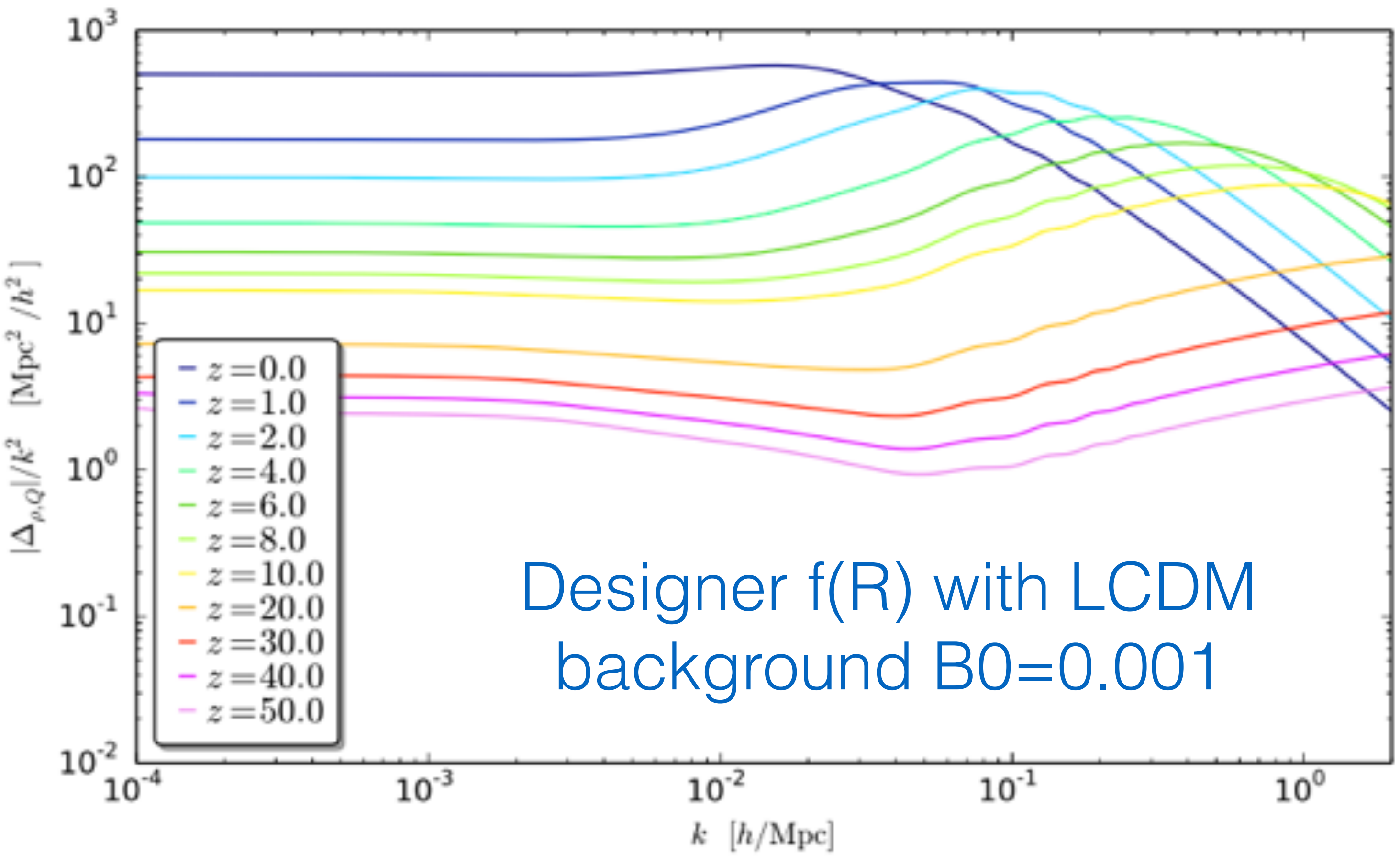
$$\delta\rho_Q^{(\mathrm{syn})} = \frac{1}{(1+\Omega)}\Big\{ -\Omega\delta\rho_m^{(\mathrm{syn})} + \dot{\rho}_Q \pi + 2c(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})}) - \frac{2m_0^2}{a^2}\left[\frac{\dot{\Omega}}{4}\dot{h} + \frac{\dot{\Omega}}{2}\Big(3(3\mathcal{H}^2 - \dot{\mathcal{H}})\pi^{(\mathrm{syn})} + 3\mathcal{H}\dot{\pi}^{(\mathrm{syn})} + k^2\pi^{(\mathrm{syn})}\Big)\right]\Big\}$$

$$(\rho_{\mathrm{DE}} + P_{\mathrm{DE}})\theta_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\Big[-\Omega(\rho_m + P_m)\theta_m^{(\mathrm{syn})} + (\rho_Q \ldots + \frac{2m_0^2}{a^2}k^2\dot{\Omega}(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})})\Big] \ ,$$

$$\delta P_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\Big\{ -\Omega\delta P_m^{(\mathrm{syn})} + P_Q\dot{\pi}^{(\mathrm{syn})} + (\rho_Q + P_Q)(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})}) + \frac{m_0^2}{a^2}\left[\frac{1}{3}\dot{\Omega}\dot{h} + \dot{\Omega}\ddot{\pi}^{(\mathrm{syn})} + (\ddot{\Omega} + 3\mathcal{H}\dot{\Omega})\dot{\pi}^{(\mathrm{syn})} + \left(\mathcal{H}\ddot{\Omega} + 5\mathcal{H}^2\dot{\Omega} + \dot{\mathcal{H}}\dot{\Omega} + \frac{2}{3}k^2\dot{\Omega}\right)\pi^{(\mathrm{syn})}\right]\Big\}$$

$$(\rho_{\mathrm{DE}} + P_{\mathrm{DE}})\sigma_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\left[-\Omega(\rho_m + P_m)\sigma_m^{(\mathrm{syn})} + \frac{m_0^2}{3a^2}\dot{\Omega}\Big(\dot{h} + 6\dot{\eta} + 2k^2\pi^{(\mathrm{syn})}\Big)\right]$$

Transfer function of Q-fluid



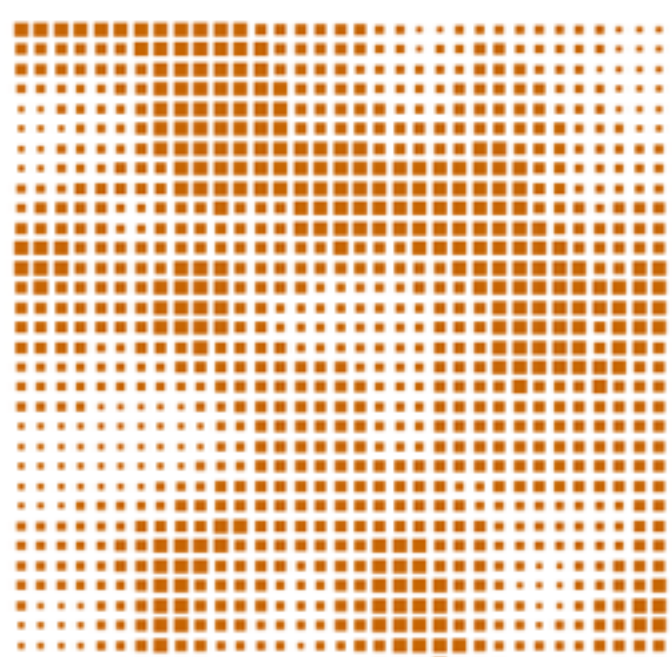
Take Newtonian limit

$$-k^2\psi = \frac{16\pi G}{3}\delta\rho_{\rm cdm} - \frac{\delta R}{6}\,.$$

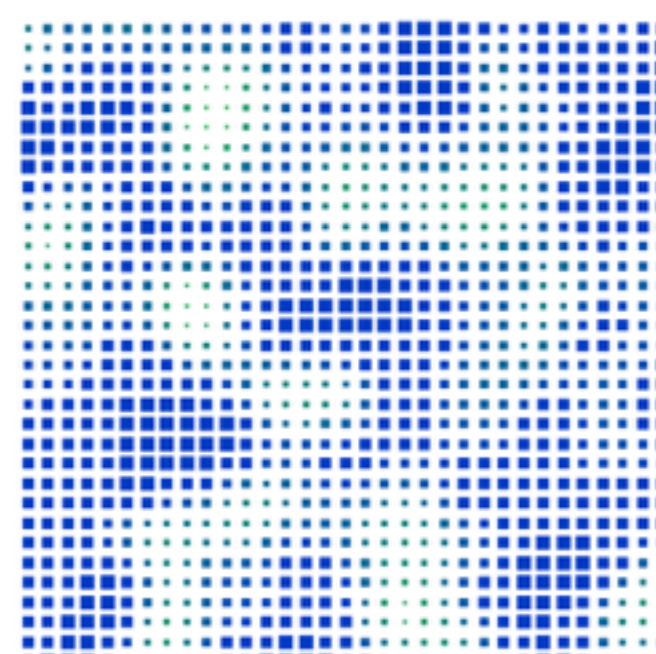
$$-k^2\psi = \frac{16\pi G}{3}(\delta\rho_{\rm cdm} + \delta\rho_Q)$$

$$\delta\rho_Q \propto -\delta R$$

In the CDM over dense regime, Q-fluid is under dense!

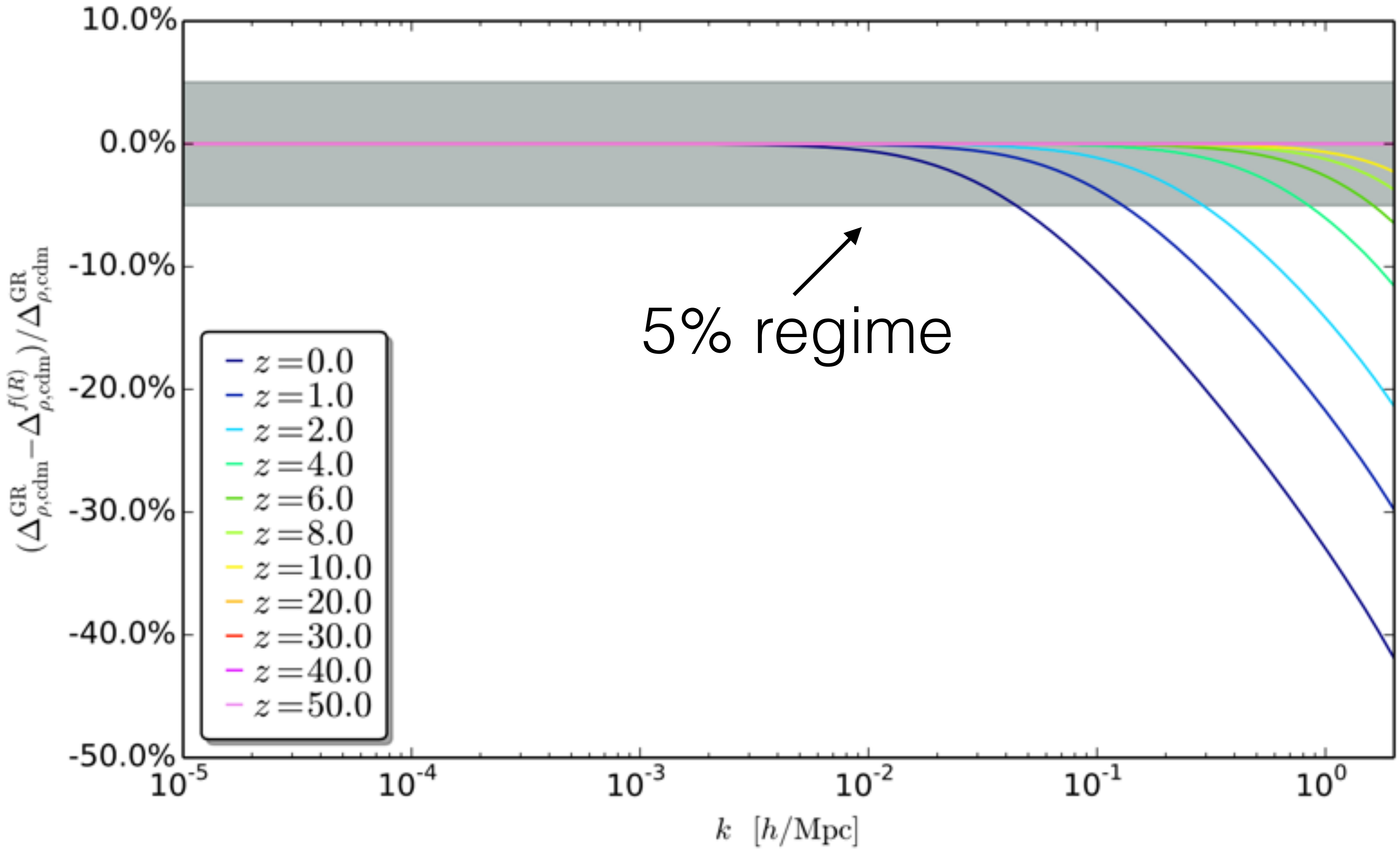


Dark Matter (Eulerian)

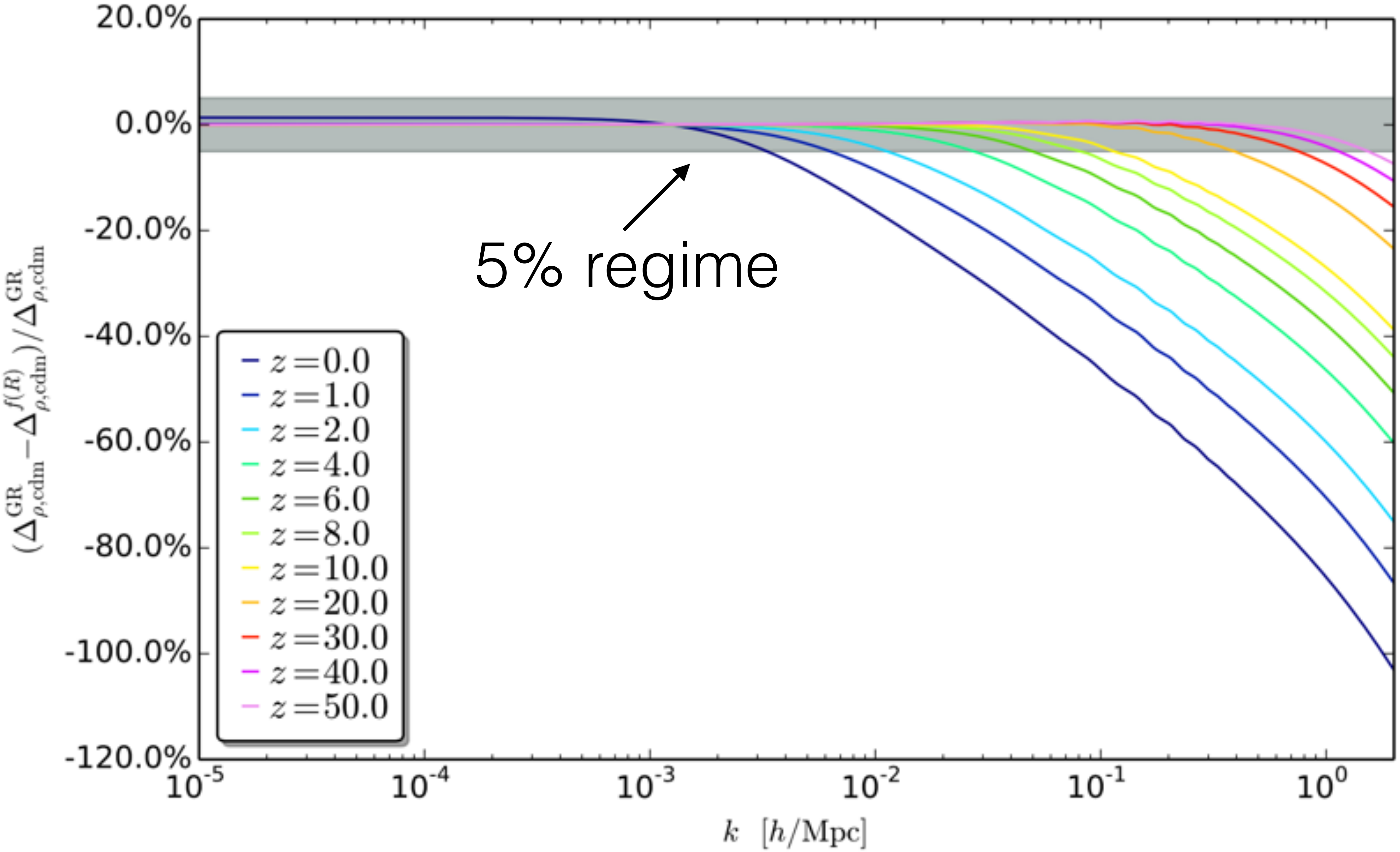


Q-fluid (Eulerian)

Transfer function of CDM

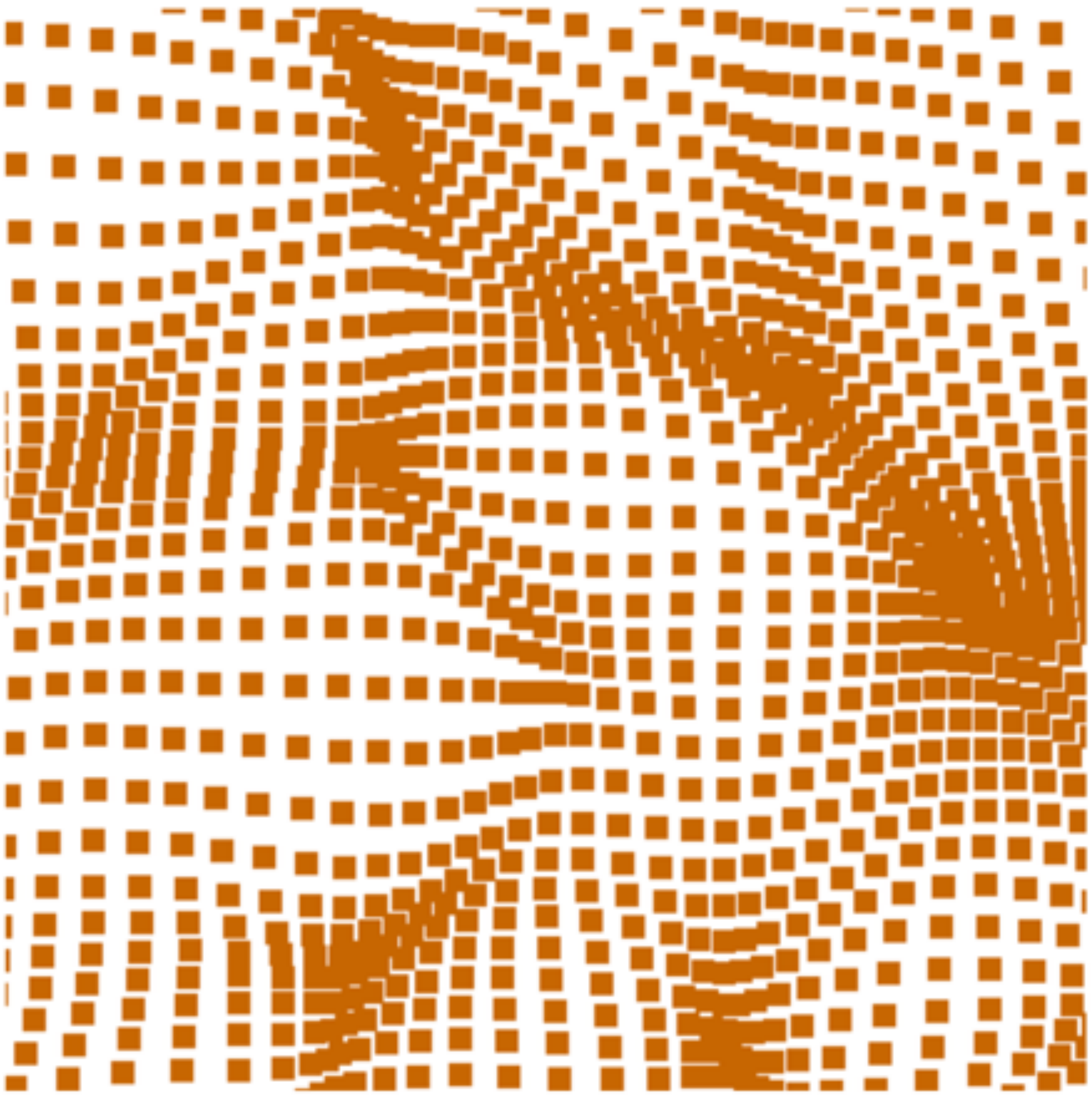


Designer f(R) with LCDM background
B0=0.001

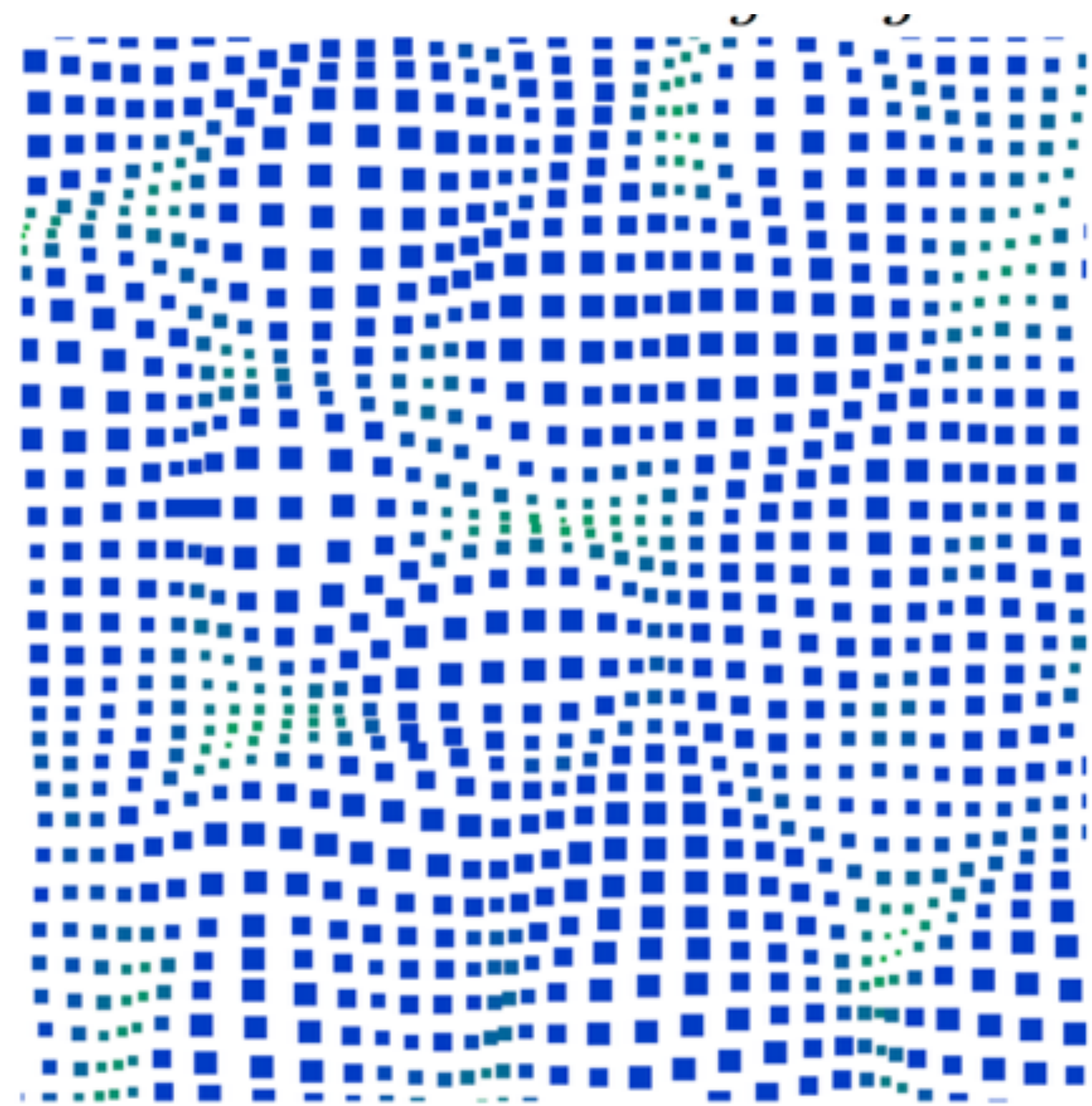


Designer f(R) with wCDM background
B0=0.01 and w=-0.95

(box size -> particle mass) (box color -> pressure)



Dark Matter



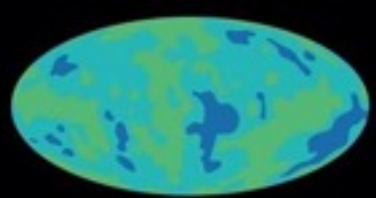
Q-particles (Langrangian)

- CDM particle mass is conserved, Pressureless
- Q-paricle mass is non-conserved, Pressure

Conclusion

- The EFT of Cosmic Acceleration provides a generic and powerful framework to efficiently study DE/MG
- The EFT framework has been implemented in the Einstein/Boltzmann code CAMB, EFTCAMB (HiCLASS, E. Bellini, M. Zumalacarregui et. al.)
- EFTCAMB is publicly available, does not rely on QSA
- XC is a valuable complementary probe for DE/MG test
- IC for N-body can be important for some DE/MG

EFTCAMB



KEEP
CALM
AND
TEST
GRAVITY

the EFTCAMB team

Thank you!